Exploring QCD at High Energy Density

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Introduction

One of the fundamental tasks of modern Nuclear Physics is the understanding of the structure of the vacuum, and the long distance behavior of the strong interactions. Quantum Chromodynamics (QCD) is the present theory of the strong interaction in the context of the Standard Model of particle physics. However many of the primary features of our universe are not easily understood from the form and symmetries of the Standard Model. Rather they result from the complex nature of the vacuum. QCD's long distance behavior gives rise to a quark gluon condensate filling all of space, constituting the QCD vacuum. This vacuum, in turn, give rise to a variety of remarkable phenomena - the confinement of quarks into hadrons, the binding of nucleons in the nucleus, the relatively large mass of the hadrons as compared to the light quarks, and conditions in the early universe about a micro-second after the Big Bang.

The vacuum, as described by Quantum Chromodynamics (QCD) consists of gluonic and $q\bar{q}$ condensates. The masses of the u and d bare quarks is of the order of a few MeV. A proton, made of primarily 3 of these quarks weighs about 300 times the mass of a bare quark. The majority of the mass of a proton comes from its coupling to the QCD vacuum. This structure is also responsible for the confinement of chromo-electromagnetic fields, which restricts all matter into coherent color singlets when viewed at a scale greater than 10^{-15} meters. At this scale the symmetries of the Standard Model are broken, and not immediately obvious through experimental observation. The underlying (chiral) symmetries of the Standard Model should be restored when the vacuum condensates melt at temperatures exceeding 170 MeV. At these temperatures matter should behave as a plasma of nearly massless quarks and gluons, a state existing in the first microseconds after the big bang.

QCD predicts that a system of quarks and gluons will have a complex phase structure, similar to that of many other bulk materials, such as ordinary water, which exhibits the well-known phases of solid, liquid, and gas with its accompanying phase transitions. The QCD phase diagram is shown in figure ?. The phase structure of the vacuum state is along the vertical axis. Two manifestations of the phase transition are thought to exist. The first is that of deconfinement, when the quarks and gluons become free of the their bondage into protons and mesons, and able to roam over large distances exhibiting the properties of a gas. The second manifestation is that of chiral symmetry restoration in which the masses of the quarks are reduced to their bare quark values. It is unclear whether these two phenomena happen under exactly the same conditions of pressure and temperature.

In recent years, theorists have made major advances in the understanding of cold quark matter at high density, at the far right of figure ?. In this very dense but very cold environment quark matter displays many characteristics more familiar to a condensed matter physicist than to a plasma physicist: Cooper pairs form, and the quark matter becomes a color superconductor, characterized by Meissner effects and gaps at the quark Fermi surfaces. Cold quark matter may exist in the centers of neutron stars and we can hope that it will become possible to use astrophysical observations of neutron star phenomena to learn whether or not they feature quark matter cores. Ultimately, we must fit together the picture of cold dense quark matter gained from astrophysical observation with the picture of hot quark-gluon plasma that we hope to gain from experiments at RHIC into a coherent, unified phase diagram for QCD.

The core heavy ion program at RHIC ushers in a new era for studies of the most basic interactions predicted by QCD in bulk nuclear matter at temperatures and densities great enough to excite the expected phase transition to a quark-gluon plasma. As this program matures, experiments at RHIC will provide a unique window for detailed studies of the hot QCD vacuum, with opportunities for fundamental advances in the understanding of quark confinement, chiral symmetry breaking, and, very possibly, new and unexpected phenomena in the realm nuclear matter at the highest density.

In concert with these studies, the RHIC spin program is expected to carry out decisive measurements of the spin structure of the nucleon. In an experimental program that is completely integrated and compatible with the heavy ion experiments, the capability to study polarized proton collisions at collider energies will allow the proton spin structure to be studied with perturbative QCD probes—allowing the collisions to be interpreted unambiguously as interactions of polarized quarks and gluons. Specifically, these studies should give direct measurements of the contribution of gluons and sea quarks to the spin of the proton, results that are not accessible to deep inelastic lepton scattering experiments.

By colliding heavy ions at extreme energies, mesoscopic regions of sufficient energy are created with conditions favorable for melting the normal vacuum and creating this novel state of matter. With the unique ability to collide beams of ions from protons to gold, and with center of mass energies from 20 to 100 GeV per nucleon, RHIC addresses a number of fundamental questions:

What are the properties of matter at the highest energy densities? Is the basic idea that this is best described using fundamental quarks and gluons correct?

Can we locate signatures of phase transitions occurring as the hot matter cools? What signatures can be calculated with perturbative QCD? What is the origin of confinement and chiral symmetry breaking?

What are the properties of QCD vacuum?

Achievements Since the Last Long Range Plan

The US program in Relativistic Heavy Ion Physics has a long history, starting with work at the Bevalac and continuing to the AGS, with a large contingent of the US community participating in the CERN program. A new frontier has now begun with the initiation of the RHIC program giving us an increase in center of mass energy of almost an order of magnitude. It is important to understand that the fixed target at the AGS and CERN on one hand, and collider experiments at RHIC and the LHC are studying rather different regimes on the QCD phase diagram as shown in figure *f1.0* The fixed target experiments have studied systems of high baryon density. At CERN, a somewhat lower baryon density but higher energy density was observed than at the AGS. In contrast, heavy ion collisions at RHIC and the LHC take us into the regime where the net baryon density of the system is very low. This situation of particular interest because it is, essentially, a high temperature vacuum.
In addition theoretical calculations, both analytical and lattice gauge calculations have improved – lattice calculations have enabled theoreticians to calculate, with more certainty, the location of the phase transition.

AGS and CERN programs

QCD has yielded its secrets up slowly. Even in the perturbative regime, the physics community did not immediately accept experimental evidence for gluons. A number of expected signals of quark gluon plasma formation have been observed in fixed target experiments at CERN (and some at the AGS), but the evidence is not yet unambiguous. The most important of the results from CERN and the AGS are reviewed here. It is important to note that there were no lepton measurements done at the AGS. A more complete review can be found in …. NRC review of Nuclear Physics…Studies of particle abundances and spectra, as well as Bose-Einstein correlations (which give information about the space-time evolution of the collision) from the AGS and CERN indicate that the system undergoes a state of rapid expansion and is close to both chemical and thermal equilibrium*. (perhaps include a figure: equilibrium+HBT+flow with lots of explanation)*
Thermal equilibrium is thought to be reached very rapidly, but standard hadronic cross sections have difficulty accounting for the rapid rate at which this thermalization occurs. However, interaction cross sections arising from color among quarks are larger and could drive rapid thermalization.

A state of free quarks is expected to show a strong enhancement of strangeness, particularly of anti-strange particles, whose yield would ordinarily be kinematically be suppressed by their relatively large masses. Experiments at CERN, in particular WA97 see enhanced strange anti-baryon production, with increasing enhancement with each additional unit of strangeness. (*Figure ?)* Experiments at the AGS, which have been able to detect only the anti-lambda, see a very strong enhancement in the anti-lambda to anti-proton ratio. Thus far, standard hadronic models cannot reproduce these results.

In 1986, Matsui and Satz suggested charmonium as a probe of the hot medium created in relativistic heavy ion collisions. A colored medium (i.e. a deconfined one) would break up a $c\bar{c}$ quark pair created by hard nucleon-nucleon scatterings, thereby causing the charmonium state to "melt". The melting depends on the energy density of the medium and the species of charmonium being considered, with the less tightly bound χ and ψ' states breaking up at lower energy densities than the J/ψ. NA50 observed just such an effect as shown *in figure ?. (again a figure with lots of explanation)* Theoretical and experimental work was required to separate initial state effects on charmonium formation, final state breakup by ordinary hadronic matter (as observed in p-nucleus collisions, for example) and the medium effects of interest.
J/ψ suppression signals deconfinement. Signatures that may be interpreted as evidence of chiral symmetry restoration were also seen. *Figure ?* shows the dilepton spectrum measured by NA45 at CERN, together with the expected spectrum from hadronic decays (again a figure with lots of explanation). The excess lepton pair yields at invariant masses between 200 and 800 MeV can be explained as a broadening and mass shift of the ρ meson due to the onset of chiral symmetry restoration. Competing interpretations of the data as arising from thermal radiation are also possible.

The fixed target experiments have certainly proven that heavy ion collisions create high energy and baryon densities. The density of hadrons is so large, that there is simply not enough room for them to co-exist as a superposition of vacuum state hadrons. The observed signatures are not readily explainable by standard hadronic models. It is also clear that a great deal remains to be done in the CERN/AGS energy regime. A new experiment NA6i is now under construction at CERN to measure the charm production cross-section, necessary to resolve questions in interpretation of the dilepton results. Other laboratories in Japan and Germany are contemplating construction of to further these studies. Systematic understanding of the signals, by varying the beam energy for example, were hampered by the fact relativistic heavy ion work at both CERN and the AGS shared running time with other programs. One of the critical lessons for the Relativistic Heavy Ion community in the US is that a commitment to a thorough study using a dedicated machine is imperative. A systematic measurement of multiple signatures in p-p, p-nucleus and nucleus-nucleus collisions is a prerequisite to a clear and unambiguous physics conclusion.

First glimpses from the initial run of RHIC

(This section assumes that the LRP will come out in Oct in the middle of the run)
The Relativistic Heavy Ion Collider, RHIC, which began construction in 1991, was completed and commissioned in the summer of 2000. The first data taking run lasted for 3 months, during which the machine reached 10% of design luminosity at 130 GeV/nucleon center of mass energy in Au-Au collisions. A successful commissioning of polarized protons was also done with protons in one ring of RHIC. First data taking with polarized proton collisions will begin during in 2001. A second run of the collider started in June of 2001 and will complete in early 2002. The machine has now reached the designed luminosity of $2x10^{26}$ $cm^{-2}s^{-1}$ at an energy 200 GeV/nucleon in the center of mass for Au ions. The first of the polarized proton runs will take place during this run.

The detectors, which were only partially instrumented for the first run, are substantially complete. Both STAR and PHENIX have a continual set of upgrades extending their capabilities. PHENIX will be adding a second muon arm and STAR will be completing their electromagnetic calorimeters and adding TPC's at large rapidity. PHOBOS is investigating options to complement its present setup with electron identification detectors originally developed for the CERN heavy-ion program. All were equipped with identical zero-degree calorimeters for to determine the impact parameter, or centrality, of the collision and allow selection of identical classes of events in all four detectors. The detectors are shown *in figure ??.*

The following will become figure captions:

STAR is a large acceptance detector built around a central Time Projection Chamber (TPC) in a solenoidal magnetic field. Inside the TPC is a silicon vertex tracker (SVT) for detecting secondary vertices. An electromagnetic calorimeter (EMCAL) and forward TPC's are being installed in the next few years. A small acceptance RICH detector for high momentum particle ID will be replaced in the next several years by a TOF system.
The PHENIX detector is composed of 4 spectrometers optimized for detecting and identifying electrons, muons, photons and hadrons in a limited pseudorapidity range. Multiple detector subsystems are used in the two central arms, yielding good momentum resolution and particle identification. Of particular note is redundancy in electron identification capabilities, giving a total e/π rejection of better than 10^{-4}. Excellent hadron identification via Time Of Flight (TOF) is available over a small angular range. Muons are detected in two arms covering forward and backward rapidities, where the muons have a kinematic boost enabling them to be separated from the copious hadrons produced in the collisions.

PHOBOS, one of the two smaller detectors, is primarily composed of silicon and is optimized for large event rates. It consists of a central two-arm spectrometer, allowing for measurements at very low-pt, and a full acceptance multiplicity array. High-pt particle identification is provided by a TOF system.
BRAHMS specializes in measuring the fragmentation region of the collisions. It is composed of two spectrometers, each with a rather small aperture, which rotate thereby allowing the detector to cover a large rapidity region by combining data from runs with the detectors in various positions.

In the 2000 run, about 10M events were collected between the 4 detectors with RHIC operating at 65GeV per nucleon, allowing for a good start on the physics program. About 2 orders of magnitude more events are expected in 2001.Analysis of the data has taken place in a timely fashion, and already much has been learned about heavy ion collisions at RHIC energies.

The particle density in central gold-gold collisions in the hottest mid rapidity region, per participating beam nucleon, is about 70% higher than at CERN (PHOBOS, PHENIX, STAR). This means that already at 65% of RHIC's design energy, the created energy density is at least 70% higher than previously attained at CERN. In the most violent collisions more than 6000 particles are produced (PHOBOS), and for the first time in heavy ion collisions a clear central plateau is seen (PHOBOS, STAR), yielding important information on the space-time aspects of the collision and particle production process. Furthermore the yield per participant increases with centrality (PHENIX, PHOBOS) indicating the importance of multiple collisions and hard processes. A measurement of the transverse energy distribution by the PHENIX collaboration shows a similar behavior. Depending on the thermalization time, the data imply that the energy density is considerably higher at RHIC than at CERN. The azimuthal asymmetry of particle production in peripheral and semi-central collisions, known as elliptic flow, is found to be surprisingly large;v2 ~ 6% (STAR, PHOBOS, PHENIX). This is interpreted as evidence that a high degree of thermalization takes place early in the collision and that there is built up of high pressure. At central rapidity the baryon to antibaryon ratio approaches unity (STAR, BRAHMS, PHOBOS, PHENIX) indicating that the quantum numbers of the hot system are approaching that of the vacuum. Bose-Einstein correlation studies have yielded size parameters of approximately 6 fm (STAR), surprisingly similar to that measured at CERN.

One of the most intriguing results comes from a measurement of the neutral pion pt spectrum. High pt particles are expected to be leading particles from quark and gluon jet fragmentation. A fast moving colored parton (quark of gluon) is an ideal probe of hot nuclear matter. In normal nuclear matter, a quark would experience only a small amount of energy loss; hence a jet would essentially carry the energy imparted to the original struck parton. In a quark gluon plasma, the deconfined color fields would slow the quark down considerably ~ energy losses can be as much as 10 GeV/fm. High pt particles would be strongly suppressed in nucleus – nucleus collisions in which a QGP were formed in comparison to a pp collisions. Figure 2.0 shows a ratio between p^0's measured in central Au-Au collisions in PHENIX and p^0's in pp collisions scaled by the number of binary collisions. The ratio is significantly less than one. The usual nuclear "Cronin" effect is expected to enhance this ratio above one. Whether this is a definitive signal of a QGP is yet to be determined. Future data will give more statistics and higher pt, as well as proton nucleus data for comparison.

One of the most intriguing results comes from measurements of high pt particles (PHENIX, STAR). The high pt particles reflect high-energy quarks and gluons that were scattered in the early stages of the collision process. They serve as useful probes of the medium through which they pass. The intriguing feature is that there are indications that the higher is the energy of the quark or gluon the more energy it loses in the hadronic medium produced in the collision. Such behavior is predicted by QCD for the passage of quarks and gluons through a high-density medium.

The interpretation of all these facts in terms of the temperature, entropy production, and ultimately on the existence of a phase transition will take some time. Early results on charmonium suppression, dilepton spectra, and multi-strange anti-baryons will require data to be taken during the 2001-2002 year. In any case this has been a spectacular beginning for the RHIC experiments.

Scientific Opportunities

The First 5 years

The Relativistic Heavy Ion Collider has just begun its task of uncovering the secrets of QCD. Detectors have been completed only recently, and the second run is about to begin. The next five years should yield a wealth of new information. In order to realize this promise it is critical that *the highest priority is to run RHIC at the full 37 weeks per year. Sufficient running time is required to realize the physics promise of RHIC and reap the rewards of our investment in RHIC's construction. Certain short-term upgrades will be necessary as well as R and D for major upgrades to the machine luminosity and to the detectors.*

37 weeks per year of RHIC operation is imperative over the next 5 years. This will allow collection of a large set of both heavy and light ion collisions for accurate measurement of low cross section phenomena, such as multi-strange baryon spectra, J/ψ, and jet production and suppression. Establishing the existence of a phase transition from hadrons to deconfined plasma requires systematic scans in collision energy and beam particle to vary the initial temperature and system size. For each beam combination and energy a high quality measurement of the potential plasma signatures must be made, necessitating 5-10 weeks of running for each case. RHIC must measure those probes of the hot medium which have produced the intriguing yet inconclusive results at CERN; many of these have small production cross sections, e.g. J/ψ and jets, so long runs will be required.

Unambiguous establishment of new physics also will rely upon "control" measurements of the same observables in elementary nucleon-nucleon collisions and in cold nuclear matter, studied via proton-nucleus collisions, at the same energy in the same detectors. High quality measurement of spin observables, such as ΔG, the fraction of the nucleon's spin carried by the gluons, requires polarized proton-proton collisions for at least 10 weeks per year over multiple years. Similar requirements on p-p and p-A running follow from the requirement that the measurements of rare processes in these reactions be of sufficient statistical accuracy to serve as comparison data sets for the heavy ion program. In addition to the all-important systematic comparison for nucleus-nucleus collisions, proton-nucleus studies will provide critical information on the parton distribution functions in nuclei, which determine the initial conditions achievable at RHIC. Lastly, machine development time is needed to reach the design luminosity and energy, establish running conditions with different beam combinations, collide polarized protons, and commission proton-nucleus collisions. Adding this to the various runs described above indicates that 37 weeks per year of RHIC operations over the coming 5 years will be just adequate for achieving the basic physics for which RHIC was built.

Given enough running time, the experiments will seek to answer specific questions which lead to the answers of the more general questions listed above.

1. What are the gross properties of dense QCD matter? Is the idea that this is best described using fundamental quarks and gluons correct?

Experiments probe these questions via measurement of hadrons - single particle distributions and correlations among particles, and by detecting penetrating probes, which interact only electromagnetically and therefore escape the dense system relatively unperturbed. Two-particle and multi-particle correlations reflect the dynamics of the dense matter, driven by pressure and density developed early in the collision. Hard scattering processes take place in those collisions between quarks or gluons (partons) in the initial state, before any thermalization can take place or quark-gluon plasma can be formed. In vacuum, hard scatterings produce either jets of particles with high transverse momenta or heavy quarks like charm or bottom, of which a small fraction materialize in bound $c\bar{c}$ or $b\bar{b}$ states. Since the initially scattered partons must traverse the full space-time evolution of the reaction, they can serve as probes of the dense QCD matter. In particular, their energy as they traverse the dense matter yields information about the medium. As jet production can be calculated quantitatively with perturbative QCD, the observed abundance and properties of high- p_t hadrons and heavy flavors will reflect the dense matter they encounter.

It would be of great interest to determine the equation of state of the hot vacuum experimentally. Lattice gauge theory predicts nearly zero compressibility for an extended range of energy densities as matter is converted into the new phase, whereas once fully converted into the new phase the compressibility should jump to the plasma value of 1/3. A latent heat is expected to accompany this transition and has significant astrophysical implications. It is an important goal of the next few years to establish a better connection between modeling of the collisions and the measurements. Measurement of collective dynamics via multi-particle correlations, such as used in flow analyses, can yield information on the pressure achieved and thereby the compressibility. Thermal radiation of photons or dileptons reflects the temperature history of the system.

2. Does the matter approach thermal equilibrium? Which partons thermalize and which do not? If thermalization is achieved, what is the initial temperature?

Real photons and virtual photons materializing as electron or muon pairs are radiated from the hot, dense QCD matter. While such radiation is emitted at all times during the collision, the reaction dynamics favors emission from the hottest part of the colliding system. Thus, measurement of the distribution of thermal radiation will yield the initial temperature. Such measurements require high statistics to separate the thermal radiation from large photon and lepton backgrounds arising from decays of the copiously produced hadrons. Systematic analysis, and variation of the initial conditions will be required to nail down the interpretation.

Measurement of the hard scattering processes via high p_t hadrons and heavy flavor distributions will indicate to what extent the fast particles lose energy in the dense medium. This energy loss results in energy transfer from fast particles to the medium and drives thermalization. Furthermore, this energy transfer multiplies the number of gluons and therefore drives particle production, increasing the density of the medium further. In fact, predictions exist that the matter may reach the stage of gluon saturation – in such a case the physics is determined by interactions in a dense gluon gas, calculable using perturbative QCD, with subsequent hydrodynamic expansion. Measured particle yields, spectra and correlations to transverse momenta of at least 10 GeV/c p_t are needed to see whether such predictions are correct. Presumably, particles with extremely high momenta will never thermalize, providing a built-in control measurement; the hadron p_t spectra and correlations among fast hadrons will indicate at which point this becomes true. Momentum and flavor distributions of the hadrons provide information on the degree of thermal and chemical equilibration when the colliding system becomes dilute enough that hadronic strong interactions cease. Combined with information from the medium probes and thermal radiation, the space-time evolution of the entire collision can be inferred. An important goal at RHIC is to determine whether equilibration occurs early in the collision, or only later, in the cooler hadronic phase. Combining hadronic observables with collective behavior reflecting early conditions, and thermal emission of virtual and real photons will become possible with the suite of experiments at RHIC.

3. How does the later, hadronic phase of the collision evolve? Can we accomplish a reconstruction of the reactions overall evolution through spectra and correlations?

Extensive study of heavy ion collisions at lower energy at the BNL AGS and CERN SPS have shown that the analysis of the distributions and correlations of soft hadrons yields the temperature and dynamics at the time the hadrons cease to interact, or "freeze out". The space-time evolution thus measured is crucial to understanding the collision dynamics and to lending confidence in back-extrapolations to the early, hottest, phase of the collision. Systematic study of the conditions under which the hadrons freeze out, as a function of initial temperature and collision volume, will help to understand the underlying dynamics and sort out signatures of new physics from the underlying hadronic processes.

4. Which signatures might indicate the new physics? Can evidence be found for the restoration of chiral symmetry?

Chiral symmetry is broken through the creation of a vacuum scalar condensate that couples to baryons and provides most of the mass for hadrons. The challenge for RHIC measurements is to search for evidence of in-medium mass changes of the low mass vector mesons associated with the restoration of chiral symmetry. Hints of this have been observed at the SPS, but a systematic study varying the initial conditions and system volumes has not yet been possible.

The presence of a phase transition from quark-gluon to hadronic matter as the system created in a RHIC collision cools is expected to cause fluctuations, which may perhaps survive the hadronic phase as fluctuations in particle number and type. A variety of fluctuations have been proposed to result from the transition. If the transition is first order, the growth of hadronic droplets and the shrinking of quark-gluon droplets may yield a lumpy final state and consequent large fluctuations in particle number as a function of rapidity. If the transition is a smooth but sufficiently rapid crossover, domains of misaligned chiral condensate may be excited. If the transition occurs near a critical point separating first order behavior from crossover behavior, long wavelength fluctuations imprint unique signatures via fluctuations of the momenta of soft pions. Experiments should search for such fluctuations, and correlate their appearance with other quark-gluon plasma signatures.

Other promising signatures include J/ψ suppression, strangeness enhancement particularly of hadrons carrying multiple strange quarks, all that have shown intriguing hints, consistent with quark gluon plasma formation at the CERN SPS. It is crucial to cross correlate the conditions under which the signals appear in order to rule out proposed hadronic explanations and prove that new physics is the ONLY consistent explanation. This necessitates experiments measuring multiple signatures, sufficient statistics and good systematic understanding of even the rarest ones, and good cross checking of event classes across different experiments.

It is clear that many of the important measurements in the initial RHIC runs involve high transverse momentum and heavy quark production, both of which have small cross sections. Such processes require long running periods and high trigger efficiencies and data rates. High statistics are needed for hadron measurements, especially for correlations studies and event-by-event analysis to isolate special classes of collisions. The low cross sections for high $p_{t,}$ multi-strange, and heavy particles require runs of at least 5-10 weeks duration for each of several different running conditions (beam energy and beam species).

All of the statistical QCD observables, along with those that can reflect new physics, such as J/ψ suppression and jet quenching, must be studied as a function of the initial conditions. This requires running RHIC at different energies of the beams to vary the initial temperature, and with different nuclei to vary the volume of dense matter. Given the expected RHIC luminosity, known production cross sections, and data rates achievable by the experiments, a scan in either energy or beam species can be achieved in one 37 week running period.

Not much data on elementary nucleon-nucleon collisions, or on proton-nucleus collisions is available at RHIC energies. Such data are absolutely crucial as a baseline to interpretation of nucleus-nucleus data. Furthermore, the exciting physics available with polarized protons and probing parton distributions via p-nucleus collisions further drive the need to exploit this aspect of RHIC's capability. As these programs rely heavily upon the same kind of hard processes used to probe the dense matter in heavy ion collisions, the running time requirements are roughly comparable.

Opportunities – Years 5-10

The discovery of the Quark Gluon Plasma would only be the opening chapter in the story. Many advances must be made both theoretically and experimentally in order to exhaust the complexities of this system. Improvements will be required in experiments, with perhaps new experiments coming online, and the machines. Large new computers will be needed for future lattice gauge calculations as well as other computer intensive tasks. In addition, the CERN heavy ion program will be starting at the LHC in 200?. It will be a wise to make a modest investment of manpower and money so that some US participation can be possible.

For the second five-year period, we must implement significant upgrades of the collider and experiments. Such an upgrade program to increase luminosity and add *new capabilities to the experiments will allow in-depth pursuit of the most promising observables characterizing the deconfined state. Following the results of the R&D, a detailed plan and schedule can be made. A gradual start of construction funding would be anticipated around 2004/5. In the mean time R&D must begin to develop the technology for these upgrades*

A strong physics case for the detector enhancements can be made now and is detailed below. The original suite of detectors omitted some much needed capabilities due to limitations on the technology available at the time of their design. It has since become clear how to achieve these capabilities in the real conditions at RHIC. Moderate scale upgrades to the large detectors and/or new or reconfigured small experiments would provide the following enhanced capabilities:

- High statistics measurement of ΔG (aided by large coverage calorimetry to allow reconstruction of parton kinematics)
- Processes in heavy ion collisions which are calculable by perturbative QCD
- ($p_T > 10$ GeV/c hadron and electron production)
- Direct measurement of the gluon content in the hot, dense medium (via heavy mesons formed by gluon fusion)
- Several kinds of control measurements to understand J/ψ suppression (observation of the small b-bar bound state, $\Upsilon(1S)$, measurement of open charm distributions, and increased overlap in observations by the various experiments)

Scientific Questions and opportunities in the subsequent 5 years

5. What are the best probes of dense QCD matter? What measurements constrain -quantitatively- the theoretical understanding of the properties of this matter?

It is self-evident that results from the initial RHIC running are crucial to answering this question. Analysis of the systematic scans across proposed plasma signatures, initial temperature and volume, as well as comparison to nucleon-nucleon and proton-nucleus data is absolutely necessary to pinpoint which probes are most sensitive. After the next year or two of RHIC running, we will be able to focus better among the various proposed medium probes.

6. What is the gluon field inside a heavy nucleus?
6b) what are the implications for formation of new physics probes?
6c) what are the implications for physics of hot, dense matter?
Gluonic interactions may be expected to dominate the first few fm/c of the collisions, immediately following the initial nucleon-nucleon interactions as the nuclei penetrate one another. Gluon fusion processes dominate the production of charm and bottom quarks, as well as drive W production at energies attainable at RHIC. Consequently, measurements of open charm and bottom decays will likely be the most important ways to study the gluon fields inside heavy nuclei and their excitations in heavy ion collisions. The Drell-Yan process of quark-antiquark annihilation probes the quark structure functions. Achieving adequate luminosity and detector acceptance to measure this at RHIC will be an invaluable tool to study the evolution of the quark structure functions to small-x inside heavy nuclei (measurements of p-nucleus collisions will yield this information) and as the parton distributions evolve during a heavy ion collision.

7. Is shadowing a small Q^2 phenomenon? Do gluons and quark densities saturate?

The nuclear shadowing will be measured directly via Drell-Yan and other hard processes in proton-nucleus collisions. Experiments must measure, with sufficient statistics, the dimuon distributions at high mass and hadron spectra at high pt (at or above 10 GeV/c) to determine the extent of shadowing in kinematic regions accessible at RHIC. The answers feed back, of course, into understanding the initial conditions in nucleus-nucleus collisions. However, they also probe the gluon field properties directly. If the gluon and quark densities can saturate, this will affect the gluon distribution deep inside a heavy nucleus as well as the dynamics of the early stage of a heavy ion collision. Measuring the intrinsic kt via hard probes, and observing how this depends on x as well as varies with volume of the dense matter produced in heavy ion collisions can address these questions. Such measurements will require increased luminosity of RHIC for sufficient yields. They will also require upgrades of the detectors for efficient reconstruction of the hard probes.

<u>Specific Upgrade Plans</u>

STAR

If new states of matter are indeed demonstrated, then the properties of the new state(s) of matter must be established followed by an understanding of the resultant new physics. This is the goal of the second five years (2006 – 2010) of RHIC experiments. Characterization of the properties of the new state(s) of matter will require more detailed correlations between various observables and will evolve to include rare probes in STAR. It will be imperative to be able to study processes with even lower cross sections, such as those at high mass or extremely high p_t. This characterization of the properties of the new state(s) of matter will go beyond the initial correlations between observables in the soft physics realm, to an increasing dependence on hard scattering and measurements of high

p_t particles, jets, direct photons, di-jets, photon-jet correlations, particle-jet correlations, and particle-photon correlations. These will extend our understanding well into the perturbative QCD regime and allow a comprehensive understanding of parton energy loss in the medium and will provide scaling comparisons in various systems. This phase will also involve an understanding of the initial conditions of the collisions in greater detail, at higher Q^2 and lower x, by measurement of the nuclear structure functions and nuclear shadowing for different initial nuclear systems. More detailed studies of $J/\psi \rightarrow e+e-$ and $\phi \rightarrow e+e-$ decays will allow STAR to study charmonium suppression and possible effects of medium modification of resonances as a function of the energy density and system size.

These physics goals will require a luminosity upgrade for RHIC and a major upgrade to STAR (near the beginning of the second phase in 2006 - 2007). An R&D program during the early phase of RHIC is crucial in order to design, test and prototype new detectors for the upgrade and the future. The additional physics goals will also require upgrading of the RHIC Computing Facility to be able to keep up with the data bandwidths, reconstruction, and analysis of data. The major upgrade to STAR will require replacement of the time projection chamber (TPC) with a fast tracking detector with particle identification. Detailed study is still needed for the design of this new system. Extended coverage in the forward direction is also anticipated. However, significant R&D is still needed to decide upon a design of the upgrade system.

PHENIX

The PHENIX experiment will build upon its baseline capabilities to address important scientific questions beyond the reach of the current detector. The three broad areas of study in PHENIX (heavy ions, spin, and proton-nucleus collisions) impose rather similar requirements on the new detector elements. PHENIX has designed a mutually compatible set of upgrades that exploit as far as possible the robust features of the current detector.

For the heavy ion program, exciting opportunities include the following:

- Measurement of the lepton pair continuum below and above the phi (a region which should be very sensitive to thermal radiation, but which suffers from large backgrounds due to conversions and hadronic Dalitz decays),
- Charm and bottom production.
- The continuum region populated by Drell-Yan processes (well above the J/ψ mass),
- Production of upsilon and its excited states.
- Furthermore, PHENIX can measure directly the QCD energy loss, in particular via jet-photon angular coincidences.

The CERN SPS has produced extremely interesting data on excess pair continuum radiation. While this data has stimulated more than 100 theoretical papers the origin of this radiation is not yet clarified. At low masses the excess might indicate medium modifications of hadrons due to partial restoration of chiral symmetry in dense matter. A solid measurement of the continuum at RHIC requires sufficient rejection of the overwhelming combinatorial pair background from Dalitz-decays and photon conversions.

In recent years interest has focused increasingly upon open heavy flavor production in heavy ion physics. Charm and bottom quarks are ideal to probe the flavor dependence of QCD energy loss. In a quark-gluon plasma, charm and bottom may be produced thermally, and first hints of thermal c-quark production might be visible at RHIC. In addition, open charm is the best reference for charmonium production, and once both charm and bottom production is established, Drell-Yan pair production will be accessible at RHIC in heavy ion collisions. The PHENIX baseline detector can tag charm and bottom by high momentum single electrons or muons and any pair combination thereof, and these measurements will yield initial charm production cross sections. However, distinguishing charm thermal leptons could well remain inconclusive. Precision vertex tracking and electron identification to10 GeV/c is needed to provide precision charm and bottom reconstruction. These measurements will also drive upgrades in RHIC luminosity and experiment data rates.

Color screening effects associated with QGP production should be tested with Υ production. The Υ(1S) is considerably smaller than the J/ψ and should not be affected by the color screening at anticipated RHIC energy densities. The Υ (2S) size is between that of the J/ψ and upsilon 1S. Separating the Υ(1S) from the (2S) requires an invariant mass resolution better than 100 MeV (about 1%) and electron ID at p > 5GeV/c. Again, significant upgrades in luminosity will also be needed; 36 weeks of Au-Au data taking at $5\ 10^{27}\ cm^{-2}\ s^{-1}$ will yield a sample of approximately 5000 $\Upsilon \rightarrow e^+e^-$.
Extending initial information on QCD energy loss in dense matter will require detailed measurements of angular correlations of high p_t particle production, in particular jet-photon correlations to study momentum, flavor, and path-length dependence of the energy loss. In addition, comparison with p-p and p-A data will be essential.
The spin program with the PHENIX baseline detectors covers a broad range of physics but with limited kinematical coverage. The importance of kinematic coverage can be illustrated by recalling for example that the *spin crisis of the nucleon* was found simply by extending the kinematical coverage of the original EMC measurement. For PHENIX, the plan is to extend the coverage in x and Q^2 to sufficiently constrain the parton distribution functions by a global analysis of all available data sets. The first moment of these parton distributions is of special importance since it directly addresses what fraction of the proton spin is carried by gluons via the proton spin sum rule. The future program aims to extend the kinematic range and measure:

- W boson production
- Heavy flavor production
- Jet production
- Gluon distribution functions
- transversity
- Spin effects in fragmentation

Isolation cuts on leptons enhance the capability to observe W boson production. Such isolation cuts can be realized for central rapidities by additional tracking with larger acceptance over the full azimuth and $\Delta\eta = \pm 1$, while for more forward rapidities additional calorimetery could serve the same purpose.

In the baseline program heavy quark production is tagged by single leptons. To reduce the background high pt cuts have to be applied which reduce statistics and kinematic coverage. Precision inner tracking will allow recovering efficiency at lower lepton momenta by a cut on displaced vertices, thus extending the kinematic coverage. Extending the acceptance of tracking and momentum measurement will allow reconstructing jets thus opening additional high statistics channels for spin physics. Coincidences of jets with photons give access to the gluon distribution function. The enhanced capabilities to detect hadrons will also extend the kinematic range to measure transversity and spin effects in the fragmentation.

The proton-Nucleus physics program is complementary to both the heavy ion and spin physics programs. The basic questions asked are very similar to those asked in both fields and thus p-A physics provides a natural link between both fields as well as invaluable data for comparison to heavy ion results. Topics that will be addressed by PHENIX include:

- Quark and gluon contents in nuclei
- Parton density at small x
- Propagation of partons propagate through nuclei
- hard diffractive processes

Standard tools to address these issues are dileptons from the Drell-Yan process, prompt photons, photon-jet and jet-jet coincidences, as well as heavy quark production. Thus the detector required to extend the heavy ion physics program and the PHENIX study of the spin structure of the nucleon is also ideally suited for proton-nucleus physics. However, to exploit fully RHIC's unique opportunities to study hard diffractive processes requires additional equipment to tag forward-going baryons. Furthermore, extending the dimuon acceptance to forward angles is desired to enlarge the x_2 coverage below 10^{-3}. The proposed concept for a PHENIX upgrade exploits, as far as possible, the existing detectors, and is optimized for all three areas of physics study: heavy ions, spin, and p-nucleus. The essential new hardware components are precision 2π vertex tracking, enhanced electron identification and photon measurements, a second coil for the central magnets, as well as a significant improvement of DAQ rate and trigger capabilities. Presently two technical options for the vertex tracking system are under investigation, further simulations, as well as R&D will be necessary to reach the level of a conceptual design report.

The first option involves two layers of off-the-shelf silicon pixel detectors mounted within 6 cm from the beam axis to detect secondary decay vertices with a resolution of better than 40 μm. Two layers of micro-pad chambers would complete the inner tracking. Each micro-pad chamber layer would measure 2 independent points resulting in a resolution of 500 μm. With the inner chamber at 30 cm radius, momentum measurement can be provided over $\Delta\eta = \pm 1$. This inner tracking systems would be supplemented by hadron-blind detectors (HBD) consisting of proximity focusing Cherenkov counters to identify low momentum electrons and allow rejection of Dalitz pairs. Low momentum electron identification could only be provided in a field configuration with *zero field* around the beam axis, requiring construction of the second coil foreseen in the PHENIX central magnet design. Segmentation of the HBD in radial direction would allow using these detectors also for electron identification above 5 GeV/c in the *high field* configuration.

The second option has two silicon pixel detector layers, identical to the above, followed by a time projection chamber in the radial range 20cm - 60cm and covering ±30cm in longitudinal direction. Combined with the silicon tracking this device would give the necessary rapidity coverage of $\Delta\eta=\pm 1$ for spin physics. Segmentation of the readout in radial direction could yield sufficient electron identification at low momenta (<500 MeV/c) for the Dalitz rejection. Though TPC's are now very well established, this new device would need to operate at high rates and large charge densities. Considerable R&D would be required to evaluate the feasibility of the approach.
The proton-Nucleus program will require additional detectors at forward angles, namely "Roman Pot" detectors for baryon tagging and a forward muon spectrometer. These detectors are modest in scope and cost compared to the central vertex tracking system. To address the rare signals and high p_t physics higher luminosities will be needed from RHIC, along with significant modifications or extensions of DAQ and trigger. Clearly, the capabilities of the RCF will need to grow as well, to handle the higher rate of data to store and analyze.

The RHIC Accelerator Complex

The RHIC lattice allows for simultaneous operation at six different interaction regions, each with a design luminosity of 2×10^{26} cm^{-2} s^{-1} for gold beams. It is expected that this design luminosity will be reached during the FY2001 heavy ion run. A major upgrade of the luminosity will require cooling of the gold beams at 100 GeV/nucleon requiring, requiring an electron beam energy of about 50 MeV and an average beam current of about 10 mA. The electron accelerator would be a superconducting, energy-recuperating linac very similar to an existing linac operating for a free electron laser at TJNAF. With electron cooling the beam emittance can be reduced and maintained throughout the store and the luminosity increased until non-linear effects of the two colliding beams on each other limit any further increase (beam-beam limit). A feasibility study for a RHIC electron cooler has been started in collaboration with the Budker Institute of Nuclear Physics (Russia). R&D to improve high brightness electron guns and energy-recuperating linacs could start soon. Increasing the mass of the heavy ion beam from gold to uranium ions at similar bunch intensities will be possible using the Electron Beam Ion Source (EBIS) that is presently in development. These upgrades would give an increase in luminosity of about 40 over design.

The RHIC spin physics program uses the unique capability of RHIC to accelerate and collide polarized proton beams at a center-of-mass energy of up to 500 GeV and a luminosity of up to 2 x 10^{32} cm^{-2} s^{-1}. Exploitation of the physics potential of this capability will begin during the next two years, and luminosity upgrades can significantly extend the physics reach of this program. An increase in luminosity of a factor of 20 over design and an energy increase to 650 GeV in the center of mass are envisioned.

Heavy ions in the LHC, and U.S. participation in the program

As discussed earlier, the state of hadronic matter created in heavy ion collisions depends critically on the energy of the colliding nuclei. At first, as the center of mass energy increases, a state of higher and higher baryon (or matter) density is produced. At energies close to the upper reaches of the AGS or lower reaches of the SPS, conditions are reached which produce a state of maximum baryon density. For collisions of identical nuclei this maximum is produced at rest in the center of mass of the two nuclei. As the energy of the colliding nuclei is further increased the baryonic matter of the two nuclei begins to penetrate. With increasing energy the system created at rest in the center of mass of the two nuclei has fewer and fewer net baryons, but more and more energy density. By the time we reach the maximum energy of RHIC the created hadronic system has almost zero net baryon number. It is truly a region of pure vacuum, heated to a high temperature by the passage through each other of two highly relativistic nuclei. From then on, further increases in the energy of the colliding nuclei lead to larger and larger volumes of hotter and hotter vacuum.

At the higher SPS energies the produced energy density is probably sufficiently high to excite hadronic matter to near or slightly above the conditions for quark deconfinement. By the time RHIC energies are reached, almost certainly, the vacuum is heated to temperatures well above those required to produce the Quark-Gluon Plasma phase of matter. Thus, as discussed in detail earlier, RHIC is the ideal machine for unambiguously discovering the QGP, and probing the phase transition from the hadronic to the QGP phase and vice versa. It is also the first machine, which allows us to penetrate into this new QGP phase, creating volumes of quark-gluon plasmas, which are sufficiently long-lived to make them accessible to a variety of specific experimental probes. At RHIC a comprehensive experimental program addressing this exciting physics, which foresees a broad range of systematic studies and future upgrades to both the machine and the detectors, has been put into place and will dominate the US effort in this field for the coming decade.

In 2006 the construction of a new collider, with even higher energy capabilities than RHIC will be completed in Europe. It is the so-called Large Hadron Collider or LHC currently under construction at CERN. LHC is being built primarily for pp studies, however there are plans to also use it for heavy ion studies. When used as a heavy ion collider, LHC will be able to operate at center of mass energy of about 30 times that of RHIC. It will thus open up the opportunity to probe hadronic matter at temperatures well above the QGP phase transition. At the time of completion of LHC, the heavy ion community will have at its disposal two complementary first-rate tools, RHIC and LHC.

Although the focus of the US heavy ion community should be and must be RHIC, it is important for us to be able to contribute to and to influence physics at the higher energy domain of LHC. Historical experience teaches us that a large increase in available energy usually leads to surprises, and that there may be a need to study at a higher energy intriguing results observed at a lower energy.

A moderate involvement of the US at LHC, of about $10M in equipment funding over 3-4 years and commitment of about 50 US scientists (10% of the involvement in RHIC experiments), will have a significant impact on both the LHC and on the US heavy ion community. This will continue a long-standing, mutually beneficial tradition in our field for US and European scientists to participate in each other's research endeavors.

We now discuss, in a little more detail, the unique heavy ion opportunities at the LHC, followed by a brief summary of the scope of the LHC project. The following aspects are unique to nuclear collisions in the LHC energy regime: The apparent density of low-x virtual gluons in the colliding nuclei will be effectively at saturation; the incoming nuclei will act as densely packed "gluon walls" approaching each other at the speed of light. Such saturated gluon fields have the important property that they can be calculated using classical chromodynamics. It is expected that, compared to RHIC, the lifetime of the quark-gluon plasma state will be longer by an order of magnitude. The fireballs created at LHC will spend almost all of their lifetime in a purely partonic state. For the first time conditions will be such that the dominating aspects of the initial state can be described without resorting to phenomenological "soft" hadronic physics. Its low net baryon density will also get one significantly closer to the conditions of the hot matter from which the Early Universe was made during its first few microseconds.

The higher initial energy will result in the formation of more "hard probes" like jets or Upsilon at significantly higher rates and easier to detect and analyze. The combination of more probes and a larger fireball opens widely the time window available for experimentally probing the quark-gluon plasma state. Furthermore the higher energy scale makes the relevant perturbative QCD calculations more reliable. Combined pp and pA with AA measurements will provide information on the spatial distribution of shadowing at very low x, in addition to the standard "unshadowed" structure functions needed for the calibration of AA results. Larger production yields of final state particles will allow first precise event-by-event and correlation analyses.

LHC is a collider that will be able to accelerate protons up to 7TeV and several species of nuclei as heavy as lead up to 7 TeV/charge. It is scheduled to be completed late in 2006 and it is planned to operate it as a heavy ion collider one month per year. The US high-energy community has a major involvement in the project. It is presently investing $440M into the construction of the collider and its experiments. Four large detectors are under construction. One of them, ALICE, is a dedicated heavy ion experiment. Another, CMS, has incorporated heavy ion studies as an integral part of their scientific program. Although the detector designs are well advanced, significant opportunities exist to have a major impact on both the detectors themselves and preparations for data analysis.

Theoretical challenges

While the general structure of QCD is now firmly established, its properties have not yet been fully understood. The following fundamental problems are still unsolved, and are at the forefront of modern theoretical physics:

1) *Confinement*

The fundamental degrees of freedom in QCD are quarks and gluons. However, free quarks and gluons have never been observed, and the physical spectrum of particles contains only "hadrons"—color singlet bound states of quarks, antiquarks, and gluons. This property of QCD has been named "confinement"; the origin of this phenomenon is linked to the properties of the vacuum. Heavy ion collisions create a hot and dense environment in which the vacuum structure can "melt", leading to novel forms of QCD matter where quarks and gluons are no longer confined. This kind of behavior has been confirmed by numerical calculations on the space-time lattice. Further progress in the theory is imperative, and includes both new analytical methods and large—scale numerical simulations on the lattice. New lattice methods and more powerful computers would enable a breakthrough in the understanding of confinement. To investigate the consequences of deconfinement phase transitions for the experimental observables in heavy ion collisions, we will need the development of QCD based event generators and the facilities for large-scale numerical simulations.

2) *Chiral symmetry breaking*

Chiral symmetry is the symmetry between "left" and "right". It is known to be violated in the Universe; the living organisms, including the humans, are not symmetric under the transformation of left to right. The phenomenon of chiral symmetry breaking occurs also at the most fundamental level of quarks and gluons. The bulk of matter in the Universe, including humans, is made of almost massless "up" and "down" quarks. For the case of massless quarks, QCD equations of motion possess chiral symmetry. However, it is not present in the physical spectrum of hadrons, and so has to be spontaneously broken in the vacuum. The theory of this phenomenon is under active development. In hot and dense matter produced in relativistic heavy ion collisions, the chiral symmetry can be restored, equating the "left" and "right". Further theoretical progress is needed to understand the microscopic origin of chiral symmetry breaking and the mechanism of its restoration. It will include development of new analytical tools, and further progress in lattice calculations. In order to investigate chiral symmetry on the lattice, one has to be able to perform calculations with realistically small masses of quarks. This places severe constraints on the size of the lattice, and requires new methods (e.g., "domain wall fermions"), and new and more powerful computers.

3) *The origin of mass*

A related problem is how to reconcile the tiny masses of up and down withquarks with the large masses of their bound states: for the proton, inwhich in the quark model is a state of two up and one down quarks, the mass of the bound state exceeds the total mass of its constituents by a huge factor of about 50! The size of the proton also presents problema problem, since the Lagrangian of QCD on the classical level is invariant under the transformations of scale. Most likely, the origin of the hadron masses is again linked to the vacuum structure. The study of modifications of hadron masses and sizes at high densities and temperatures would allow shedding light on this fundamental problem. The progress here depends on the understanding of confinement and chiral symmetry breaking, and will require similar effort and tools.

4) *The properties of matter at the highest densities*

Relativistic heavy ion collisions produce matter at the highest densities achievable in the laboratory. Understanding the bulk properties of this matter is of great importance for the theory of strong interactions and for the physics of the Early Universe. Theoretical progress in this direction again requires both analytical efforts and the lattice simulations. At present, reliable analytical tools for the temperatures and densities attainable at RHIC do not exist; this is because perturbative expansion for the bulk characteristics of matter, such as the energy density and pressure, is badly divergent for moderate temperatures and baryon number densities. The development of new theoretical tools is clearly needed. There has been impressive recent progress in the understanding of phenomena occurring at large baryon density, such as color super-conductivity. However the lattice calculations at present can only be performed at zero net baryon density, hindering theoretical progress. New theoretical tools and large scale computing facilities are needed for a breakthrough. To aid interpretation, and help extract information about the properties of matter from RHIC experiments, an effort to develop QCD based event generators is extremely important.

5) *The high-energy limit of QCD*

The behavior of QCD at the high-energy frontier has not yet been understood. The most simple, and most fundamental, questions are still unanswered: Why do hadron cross-sections rise? How are particles produced? What is the wave function of a high-energy hadron? RHIC will help to find the answers by providing detailed data on particle production in a wide range of atomic numbers and energies. Progress in the understanding high-energy behavior in QCD will allow us to reconstruct initial conditions in heavy ion collisions, which is a crucial prerequisite for theoretical description of the entire process. It will need further development of new theoretical tools, where there has been a remarkable recent progress. It will also need large-scale real-time Monte Carlo numerical simulations.

6) *Strong CP problem*

While QCD allows for a violation of parity and charge conjugation combined with parity (CP), this violation has been never observed experimentally in normal conditions. Why this is so is still a subject of theoretical studies. It would be of great interest to check if CP violating processes are possible under extreme conditions of high temperature and density. Theoretical progress here is linked to the understanding of topological effects in gauge theories at zero and finite temperatures. This requires both analytical tools and lattice simulations. To search for the effects of anomalous parity and CP violation in experiment, one needs to incorporate these processes into the event generators.

Junk

Ten microseconds after its birth, the universe was filled with quark-gluon plasma, which then cooled through the QCD phase transition. If this transition were sufficiently violently first order, the protons and neutrons left in its aftermath would be sufficiently inhomogeneously distributed that big bang nucleosynthesis, occurring a few minutes later, would be adversely affected. If RHIC is able to show that the cosmological phase transition was not first order, this would provide further support for the conventional picture of big bang nucleosythesis. We today are made of the now cold embers of the cosmological QCD phase transition; at RHIC, by colliding the embers, we are seeking to recreate the quark-gluon plasma last seen when the fires of the big bang burned hot.